Diagnostic Techniques
for Soils and Crops

CHAPTER II

Correlation of Soil Tests with Crop Response to Added Fertilizers and with Fertilizer Requirement

By Roger H. Bray[1]

SOIL testing and the interpretations of soil tests comprise a comparatively new branch of study in soil-plant relationships. The possibilities and limitations of this phase of research, which is still in the formative stage, have not been thoroughly explored under all conditions. This chapter, therefore, represents principally the viewpoint of the writer and makes no pretense of expressing the views of all workers in this field.

MAJOR CONCEPTS IN SOIL FERTILITY

Certain major concepts have a definite bearing on soil fertility in general and on soil test interpretations in particular. These are:

1. *The availability concept.* This concept recognizes that different forms of nutrients in soils vary in their availability, and that it is often the relatively small amount of a rather highly available form which has the most influence on crop growth. *The available soil forms may be defined as those forms present in the soil, variations in the amount of which are mainly responsible for variations in yield and response to added fertilizers.* One of the major objectives in modern soil fertility studies is to measure these available forms and correlate them with crop growth and response to fertilizers.

2. *The law of the minimum.* According to Liebig's law of the minimum, the yield is limited by that factor which is at the minimum; that is (in the extreme interpretation), that factor which is present in the least relative amount or intensity is the only one which limits yields (19).

3. *The law of diminishing returns.* As developed by Mitscherlich and Spillman for plant growth, the law of diminishing returns states, in effect, that with each additional increment of a fertilizer the increase in yield becomes smaller and smaller (19).

4. *The Baule percentage yield concept.* This concept states that the final yield is the product of all the factors in yield, and not a result of a minimum factor as asserted by Liebig. Baule expressed each nutrient level in terms of ability to produce a certain percentage of the maximum yield; that is, each amount of a nutrient possesses a certain sufficiency in terms of percentage yield.

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Where two or more nutrients are deficient, the final yield is the product of the percentage yields (19).

5. *The mobility or elasticity concept.* To the foregoing concepts the writer has added the mobility or elasticity concept in soil fertility, which states, in effect, that the available soil nutrients have a variable availability which depends on the mobility of the nutrients in the soil and on the nature of the plant. Those with little mobility, like phosphorus, potassium, calcium, and magnesium, tend to follow the Baule percentage yield concept. The mobile nutrients, like nitrate nitrogen and water, tend to follow the Liebig idea of a limiting nutrient. As is explained in a subsequent section of this chapter, the mobility concept incorporates the features of each concept which have been found applicable and provides an explanation of how and why they apply.[2]

All these concepts must be thoroughly understood before any attempt is made to perfect soil tests or to correlate them with crop response or fertilizer needs.

NATURE OF SOIL FERTILITY

Modern concepts of soil fertility separate soils into two groups[2]: those which adsorb and hold in an available but relatively immobile and unleachable form the nutrients needed by plants, and those which, like some Florida sands, have no ability to adsorb soil nutrients and must be treated as though one were dealing with a culture solution. The latter are not true soils in the usual sense. The chemistry of soil fertility is not the chemistry of the culture solution, and as soils approach the stage where they can no longer hold appreciable amounts of nutrients the interpretations given in this chapter no longer fully hold. These interpretations are limited to soils that can retain and build up available supplies of plant nutrients.

Fertile soils are soils which, except for nitrogen and water, have a large reserve of nutrients already present in available forms—forms which are available to plant roots, yet are relatively immobile in the soil. Even in infertile soils, these forms are usually present in amounts many times larger than any one crop can remove.

These available but relatively immobile forms are the exchangeable bases like potassium, magnesium, calcium, and manganese; the exchangeable or adsorbed forms of phosphorus; the precipitated forms of relatively insoluble materials like calcium carbonate or the calcium phosphates. All of these can accumulate in relatively large amounts in soils. It is these amounts, which have accumulated in the past as a result of previous treatments or natural

[2] Bray, R. H. Soil nutrient status as related to the responses and yields of crops. Paper given before the American Association for the Advancement of Science, St. Louis, March, 1946.

processes, that are responsible for fertility in soils. The yearly release of nutrients from unavailable forms has, except for nitrogen, only a minor effect on the immediate crop, although it can have a major effect on maintenance of fertility over a long period.

Because these nutrients are relatively immobile, their availability to plants is limited by the nature of the plant, particularly the density and extensiveness of the rooting system. The roots must go out and forage for the immobile nutrients, continually sending out new roots as the older ones exhaust the effective feeding zone.

The relatively mobile nutrients like nitrate nitrogen and water cannot be stored in the soil: they have no available *storage* form which is independent of the season. But nature has provided an insoluble, unavailable storage form of nitrogen in the soil humus, which is liberated on a seasonal basis. Water is also provided by rainfall on a seasonal basis. When soil humus or other organic matter decomposes, the ultimate available nitrogen produced is in the form of nitrate, which is highly mobile.[3] The availability of the mobile nitrate nitrogen is not much limited by the nature and density of the root system, since this form of nitrogen can diffuse to the roots, and in the rooting area it approaches 100 per cent availability. It is because the immobile available storage forms are stored in large amounts, relative to the needs of one crop, and do not approach 100 per cent availability, that the prediction of fertilizer needs for a period of years through soil testing becomes practical.

The elastic availability of the immobile soil forms is made possible by the large amounts present. Even in a deficient soil the amounts are several times larger than can be used by a single crop. But the immobile forms have a very indefinite availability to plants. Favorable seasons, favorable physical soil conditions, and good varieties all help produce higher yields, which require the uptake of larger amounts of nutrients on any one nutrient level. It is the larger, denser, and more efficient root system produced by these more favorable conditions that makes it possible for the plant to forage for the large amounts of nutrients needed. Although variable foraging can take place at any one nutrient level, maximum yields are impossible if the level is a deficient one, since a deficient level cannot be overcome by making the other conditions more favorable. This is because the plant itself is responding to changes in other

[3]Ammonium nitrogen is relatively immobile, acting like potassium and magnesium, but is not a permanent storage form.

factors. If, for example, potassium is only 80 per cent sufficient for a given crop it will restrict yields by about 20 per cent over a wide range of productivity. The higher yields take out more potash but will still be 20 per cent lower than what could have been produced with adequate potash.

This illustrates what is meant by elastic availability of the immobile nutrients, which enables them to work with a similar percentage of effectiveness at different productivity levels. It could only work where the immobile supplies of the available forms are, even in deficient soils, in excess of the needs of any one crop. Otherwise, there could be no flexibility or elasticity in their effect on productivity while their percentage of efficiency remained constant. The Baule percentage yield concept holds only for the immobile nutrients.

The mobile nutrients, like nitrate nitrogen, are not stored in the soil in available forms over long periods and in large amounts relative to crop needs. Expansion of the root system of a plant does not, for example, increase the amount of nitrate nitrogen liberated from humus by bacterial action. It may slightly increase the ability of the plant to obtain more of the nitrate nitrogen produced. Since nitrates are mobile and, except when they are more than adequate, cannot be found concentrating anywhere in a soil under normal growing conditions, there is little reason to believe that making other conditions more favorable significantly increases the effectiveness of a given amount of nitrate nitrogen. Therefore, except where nitrate nitrogen is supplied in excess of any possible yield level, it will act as a limiting nutrient in the Liebig sense. A soil liberating only 50 pounds of available nitrogen cannot produce crops containing more than 50 pounds of nitrogen. Some elasticity of use of this nitrogen within the plant is possible, but it cannot be compared to the elasticity provided by the soil-plant relationship involving the immobile forms.

Thus both Liebig and Baule were partly right and partly wrong in applying their concepts to all nutrients. Liebig's concept holds for culture solutions where all nutrients are soluble and hence cannot possibly have an elastic availability; Baule's concept holds for all nutrients for which the plant must forage. The mobility concept helps explain why these concepts work and where they apply.

PLANT COMPETITION

With normally planted row crops, like corn or cotton, relatively little competition occurs for the immobile nutrients for which the

Does his discussion then omit P + F. crops?

plant must forage. On the other hand, the plants do compete actively for nitrate nitrogen and water, the mobile nutrients. The mobile nutrients must be shared: the fewer the plants, the larger the share for each plant. Decreasing the rate of planting does not markedly increase the supply of immobile nutrients for these row crops or for crops like wheat or oats. The reason is that no one plant can effectively make contact with all the areas in any soil and remove all the available but immobile nutrients. This leaves much of the soil area untouched by plants. Normally, competition between plants for other factors in plant growth like water and nitrogen limits growth long before competition for the immobile

TABLE 1.—RELATION BETWEEN YIELD WITHOUT ADDED POTASH* AND SOIL-TEST VALUES FOR AVAILABLE POTASSIUM

Available potassium (b_1)	*Yield without added potash*		
	Corn or clovers ($c_1 = 0.0065$)	Soybeans ($c_1 = 0.0077$)	Wheat or oats ($c_1 = 0.012$)
lbs./A.	*per cent*	*per cent*	*per cent*
40	45	51	66
60	60	65	80
80	70	76	90
100	78	83	94
130	85	90	97
150	90	93	98
200	95	97	
300	98		

Courtesy the Williams & Wilkins Co., Baltimore, Md., publishers of Soil Science

*Where yield with adequate potash is 100 per cent.

nutrients has a marked influence. A marked increase in the rate of planting row crops should be followed, however, by a change in the level of the immobile nutrients required for maximum yields. It has not yet been demonstrated how much change occurs as planting rates vary. The calibrations found by the writer, and shown in tables 1 and 2, are for the standard planting rates used on the Illinois agricultural experiment fields from which the yield data were obtained. These per-acre rates are 8,000 to 12,000 stalks of corn in 40-inch hills, 2 bushels of oats and 6 pecks of wheat drilled in 8-inch rows, and 70 pounds of soybeans drilled in 40-inch rows. Clovers were seeded at the rate of 10 pounds.

PLANT COMPOSITION

Expansion of growth which causes a decrease in the nutrient content of a plant, as does the more efficient internal utilization of nitrogen brought about by improving other factors in growth, is not always a desirable feature. Plant composition follows the growth curve (19), and plants growing on a soil only 60 per cent sufficient in phosphorus, for example, will contain less phosphorus per unit of weight than ones growing on a soil 90 per cent sufficient in this nutrient. If other factors are sufficiently improved to make the yield on the 60 per cent soil larger than the yield on the 90 per cent soil, the higher yield would still be the lower in phosphorus.

TABLE 2.—RELATION BETWEEN YIELD WITHOUT ADDED PHOSPHATE* AND SOIL-TEST VALUES FOR AVAILABLE PHOSPHORUS

Available phosphorus		*Yields without added phosphate*		
Test Reading	(b_1)	Wheat or clovers (c_1 = 0.009)	Corn (c_1 = 0.015)	Soybeans† or oats (c_1 = 0.017)
	lbs./A‡	*per cent*	*per cent*	*per cent*
Low−	36	53	71	76
Low	50	65	82	86
Low+	60	71	87	90
Slight−	70	75	91	93
Slight	80	81	94	95
Slight+	90	84	96	97
Medium−	110	90	97	98
Medium	125	93	98	
Medium+	170	97		
High−	190	98		

Courtesy the Williams & Wilkins Co., Baltimore, Md., publishers of Soil Science

* Where yield with adequate phosphate is 100 per cent.

† Estimated percentage yield values for soybeans; probably too low.

‡ Corresponding value at 1–50 soil-solution ratio.

The percentage composition should therefore give an indication of the nutrient status of the soil. But of more importance, the soil test, which reveals the nutrient status of the soil, should be a good indicator of crop composition. This is of great importance in helping to control nutrient deficiencies in animals and man by controlling nutrient levels in soils.

WHAT SOIL TESTS MUST MEASURE

Soil tests must measure the *total amounts* of the available forms of nutrients in soils (5). The old idea that a soil test must simulate

plant feeding and remove the available nutrients in amounts proportional to those removed by crops is fundamentally unsound and has led to no progress in soil fertility. A test based on this idea is, in effect, an attempt to measure the "availability of an available form." Modern concepts in soil testing have discarded this idea and replaced it with the concept that the test must measure the total amount of the available nutrient and that the crop must be allowed to indicate the significance of that amount in terms of growth and response to the added nutrient (5). Soil-testing methods which allow variable soil properties to influence the amount of the nutrient extracted can never have a "universal" application. For example, the variable base-exchange capacity found in soils can cause marked variation in the amount of exchangeable potassium extracted by a weak solution. Sufficiently strong extracting solutions are the key to successful soil-test correlations.

REQUIREMENTS FOR A SUCCESSFUL SOIL TEST

To be successful, a soil test must employ an extracting solution that meets the following requirements:

1. It must extract the total amount (or a proportionate amount) of the available form of the nutrient from soils with variable properties.
2. It must measure with reasonable accuracy the amount of the nutrient in the extract. It is of little value, however, to use a highly accurate procedure on the extract if the solution does not meet requirement 1.
3. Its action must be fairly rapid. Accuracy, however, cannot be sacrificed for speed. Before the same solution is used to extract more than one nutrient, it must meet requirements 1 and 2. Although exchangeable bases and nitrate nitrogen can all be removed with the same extracting solution, necessitating only one extraction, a separate extraction or extractions for other nutrients may be necessary.

Since there is more and more tendency to make the tests in laboratories under controlled conditions and with modern equipment such as the photoelectric photometer, the idea of the "field" test has virtually disappeared except for special uses.

Often a test may be of an exploratory nature. Perhaps the nature of the available form of the nutrient is not known, and hence the nature of the extracting solution needed must be determined by trial and error. In such cases, various kinds and strengths of extracting solutions are tried on soils of known response to the nutrient. The extracting solution whose results give the best correlation with crop response can be selected for further study and improvement. Until a test is correlated with the growth and response of a crop, however,

it must be considered as exploratory, a test suggested for possible use but not proved.

Because available nitrogen is of a mobile nature, not stored in an available form, tests for this nutrient do not have the same significance as do ones for phosphorus or potassium. Soils can produce 100 bushels of corn during the growing season, without containing at any one time more than 5 to 15 pounds per acre of available nitrogen in the surface layer. Only through knowledge of both the amount of crop growth and the soil test value can release of nitrogen by the soil be estimated. Nitrogen is an inelastic nutrient and, as such, has a special place in soil fertility studies. The elastic nutrients regulate yields on a percentage basis. Soil-test interpretations in terms of percentage sufficiency and fertilizer requirements can be accurately made only when the nutrient is immobile and elastic.

CORRELATING SOIL TESTS WITH CROP GROWTH AND RESPONSE TO ADDED FERTILIZERS

Every farmer wants to know two things about his soil:

1. How deficient is the soil in a given nutrient; that is, how much will it respond to addition of *adequate* amounts of the nutrient?
2. How much fertilizer is needed to give this response; that is, what *is* an adequate amount?

Every well-designed experiment field should provide answers to these two questions for the soil on that field. To apply this information to other soils is another problem. The idea of using the soil type as a fertility unit and applying experiment field results to other areas of the same type or perhaps similar types, has been tested and found entirely inadequate from this standpoint. The soil type is no longer considered a unit so far as available nutrient supplies are concerned. The use of soil tests, correlated through experiment field results and applied through thorough testing of each field, appears to be the most practical solution to the problem so far advanced.

But how many experiment fields are well designed? To answer question 1 requires a plot so treated that no nutrients are deficient or in harmful excess and also a plot similarly treated but with one nutrient omitted. To answer question 2 requires application of varying increments of one nutrient across plots otherwise fully treated. Many experiment fields cannot meet either requirement, being based on single-increment studies in which the increment is

supposed to represent a "practical" amount. The response to a "practical" amount of a nutrient neither measures the deficiency nor the amount of fertilizer needed to overcome the deficiency. Over a period of time, however, this "practical" amount may build up the soil, which will finally represent adequate treatment, thus furnishing data to answer question 1. But question 2 will remain unanswered until different rates of application are studied, preferably on several different nutrient levels, that is, on soils varying in degree of deficiency of the nutrient being studied.

The correlation of soil tests with crop growth and response can best be discussed by illustration.

EXAMPLE 1. CORRELATING A POTASSIUM TEST WITH CROP GROWTH AND RESPONSE

The potassium test used in this illustration is one designed by the writer and proved to *extract* and *measure* the total exchangeable (and water-soluble) potassium in soils (4, 7, 14). That the *total* exchangeable potassium as measured is the form in equilibrium with the traces of potassium in the soil solution was also demonstrated (8).

This test is as follows:

Test for Exchangeable and Water-Soluble Potassium in Soils

Reagents.

Reagent A. A neutral solution of sodium perchlorate or sodium nitrate. Weigh out 250 gm. of the salt and make up to 1,000 ml. with distilled water.

Reagent B. A sodium cobaltinitrite solution. Dissolve 50 gm. of $Co(NO_3)_2$ and 300 gm. of $NaNO_2$ in distilled water acidified with 25 ml. of acetic acid and made up to a liter with distilled water. Allow the solution to stand uncorked for 24 hours and filter into a brown bottle.

Reagent C. A 50-50 mixture of pure synthetic (water-free) methyl (99.8 per cent) and isopropyl alcohol (99 per cent). The usual 95 per cent ethyl alcohol may be used in place of this mixture. Neither methyl nor isopropyl alcohol used alone is satisfactory for this precipitation technique.

Standard potassium solutions. Solutions containing 20 and 50 p.p.m. of potassium made up in reagent A.

Preparing samples. If the samples of soil are too moist to be put through a sieve, allow them to stand drying in the bag with the tops open. When they are dry enough, put most of the sample through a 10-mesh sieve or a common flour or household sieve. Put the sieved soil into a ½-pound bag. Do not put more than 1 inch of soil into the bag; ¾ inch is sufficient. Cut off the top of the bag and then let the soil dry for 10 days, or longer if the sample was fairly moist when it went through the sieve. Samples that have not been in air-dried condition for at least 2 or 3 days will give low results. Mark all bags with the farm number and the sample number.

Making the calibration curve. The photometer is calibrated by using standard potassium solutions which are developed in the same way as the soil extract. To calibrate, use solutions containing 20 and 50 p.p.m. of potassium in reagent A. Place 12 to 15 ml. of each of the 20- and 50-p.p.m. potassium standards in tubes and cool in the cooling pan. Develop four samples of each, following the directions given under *"Developing the precipitate"* (below). After 5 minutes, read them in the photometer. Then plot these readings on semilogarithmic paper. The logarithmic values will represent the photometer readings, and the arithmetic, the concentration. For highest accuracy do not project the curve too far, as it does not follow a straight line at the extremes.

Rerun this curve every time a new cobaltinitrite solution, alcohol solution (reagent C), or other new solution is used, as variations in reagents may shift the curve. Also run standard potassium solutions each day determinations are made, to be sure the determinations check with the curve.

As long as the values for the standard potassium solutions fall approximately on the already established calibration curve, the concentrations of the soil tests are read directly from this curve.

Soil extraction procedure. Measure 5 gm. of 10-mesh *air-dry* soil (see *precautions* for obtaining *air-dried* soil, p. 61) in a 5-gm. scoop. Tap the scoop sharply with a spatula or knife three times to settle the soil. Then, with a spatula strike the soil off level with the top of the scoop. Pour the measure of soil through a small funnel into an 18- by 100-mm. flat-bottomed vial containing 10 ml. of reagent A. Stopper and shake for 1 minute and pour on a dry folded 9-cm. filter paper placed in the filter tube.

Cooling. Before developing the precipitate, cool the filtrate by placing the filter tubes in a water bath, and also cool reagents B and C. Tap water is usually cool enough. The temperature may be anywhere between 16 and 23° C. but should be fairly constant, not varying over 1 or 2° C. for any run.

Developing the precipitate. Measure 2 ml. of cooled reagent C into a very clean absorption tube. Add 6 drops of cooled reagent B and shake the tube. This will give a yellow precipitate. Fill a 2-ml. medical syringe with the cooled extract, using an 18-gauge needle.

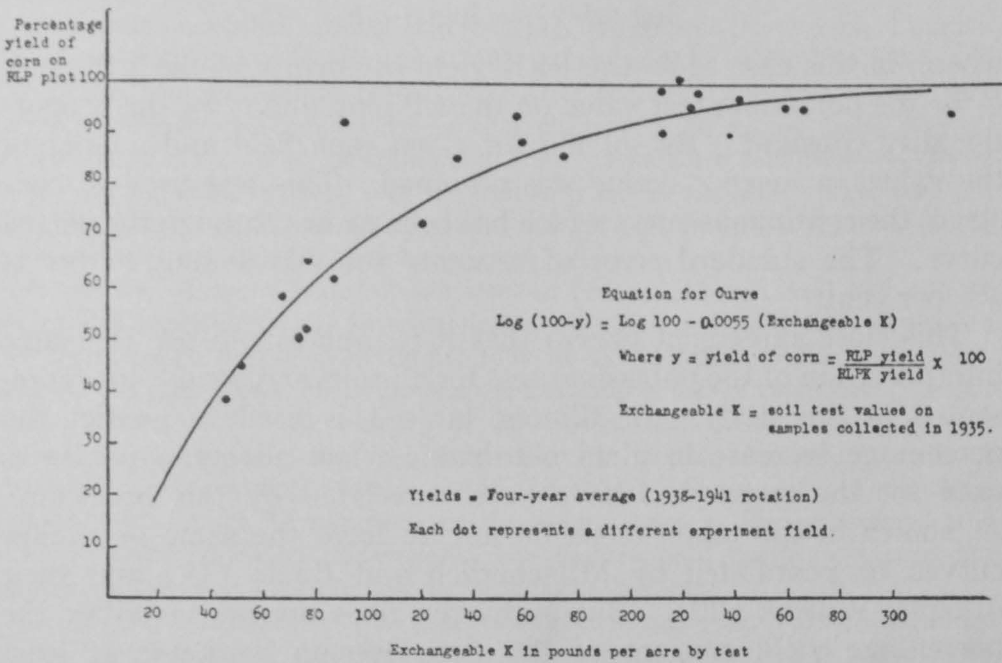
Operating the plunger with the right hand, rapidly and evenly inject the liquid into the center of the cobaltinitrite-alcohol mixture. The liquid should be forcibly injected to mix the solutions instantaneously. Do not direct the stream against the side of the tube.

Reading the precipitate. After the developed precipitates have stood about 5 minutes, and not longer than 15 minutes, they can be read in the photometer. The photometer readings are converted to parts per million potassium through the curve obtained with the 20- and 50-p.p.m. potassium solutions and multiplied by 4 to give pounds per acre. Since the precipitation varies with the operator's technique, with temperature, and with reagents, it is an arbitrary method. The standard potassium solutions must be run each day. Each operator has his own conversion chart.

A technique less sensitive to temperature variations includes use of 99 per cent isopropyl with the double-layer precipitation technique originally suggested by the writer (4).

Correlating the Potassium Test with Percentage Yield

Composite samples of the surface 6 2/3 inches from each limed and phosphated (LP) plot on 23 Illinois experiment fields were tested by the foregoing procedure, care being taken to run the tests exactly as they would be run for a routine test. These plots represent, as far as is known, soils which are fully fertile except for potassium. Adjacent to each of these plots was an LPK plot. Both series of plots had received adequate limestone (L) and phosphate (P), and green-manure legume crops were in the rotation to supply nitrogen. Crop residues were also turned under. But only the LPK plot received potassium, at the annual acre-rate of 100 pounds



Courtesy the Williams & Wilkins Co., Baltimore, Md., publishers of Soil Science

Figure 1.—Relationships between exchangeable potassium and corn yields on untreated plots receiving no K_2O

of KCl, which, according to additional studies, was adequate even on the lowest testing soils. Here we have a situation in which the yields represent the maximum so far as the nutrients phosphorus, potassium, and limestone are concerned. But each field produces at different fertility levels. To reduce these various yield levels to a common denominator, the yield on the plot without potash (LP) was divided by the yield on the potash-treated plot (LPK) and multiplied by 100. In this way, all LPK yields represent a 100 per cent yield so far as phosphorus and potassium are concerned,

and each adjacent LP yield is expressed as its percentage of that yield. For example, the 4-year average yields on the Clayton field, which tested (average of 4 plots) 158 pounds of potassium per acre, 2,000,000 pounds of soil, were 79.3 bushels of corn on the LP plots and 89 bushels on the LPK. Thus the LP yield is 89 per cent of the LPK yield.

By plotting these percentage yield values for different fields against the soil test values, the dotted curve in figure 1 was obtained. Because this dotted curve closely coincided with a typical Mitscherlich growth curve or curve of the law of diminishing returns, Mitscherlich's equation for the curve was modified to fit the situation as follows:

$$\log (A\text{-}y) = \log A\text{-}c_1 b_1$$

where, in this case, $A =$ the LPK yield of corn, $y =$ the LP yield, $b_1 =$ the potassium test value on the LP plot, and $c_1 =$ the proportionality constant. By solving for c_1 on each field and averaging the values, a mean c_1 value was obtained. This was used to construct the continuous curve which has been drawn through the dotted curve. The standard error of estimate for this average curve is ± 5 per cent.

This close agreement proves that it is practical to use the same interpretation of the potassium test for all soils and conditions represented in the study. In Illinois, table 1 is used to predict the percentage increase in yield obtainable when adequate potash is used for the crops that have been correlated by this procedure. As shown in the table, crops do not all have the same or similar curves, as postulated by Mitscherlich and Baule (19) and their disciple, Willcox (20). But each crop does appear to follow the percentage yield concept of the two German workers; at least within the conditions of the study, that is, the percentage yield of the untreated plot does represent a common denominator.

Example 2. Correlating a Phosphorus Test with Percentage Yield

The phosphorus test used in this illustration is one designed by the writer (3) and recently modified (7, 16) to measure more accurately the important forms of phosphorus in soils. In the case of phosphorus the situation is not so clear-cut as with potassium. Several different forms of phosphorus can occur in soils, each having a different availability. The test represents a compromise between the concept that the total amount must be measured and the fact that several forms, varying in availability, may be present.

But our unpublished studies show that the test does extract a somewhat proportionate amount and that the values obtained correlate at least as well with crop response as do the quantitative methods for the different forms.

This method, as adapted for the photometer by Arnold and Kurtz (1) is as follows:

Test for Adsorbed and Easily Acid-Soluble Phosphorus in Soils

Reagents.

P-A. A solution of 0.03 *N* ammonium fluoride in 0.1 *N* hydrochloric acid.

P-B. Add (with stirring) a solution of 100 gm. of ammonium molybdate in 850 ml. of distilled water to a cold solution of 160 ml. of H_2O in 1,700 ml. of concentrated HCl.

P-C. Amino-naphthol-sulfonic acid reagent. Mix thoroughly 2.5 gm. 1-amino-2-naphthol-4-sulfonic acid (Eastman 360), 5.0 gm. sodium sulfite (Na_2SO_3), and 146.25 gm. sodium bisulfite (Meta, $Na_2S_2O_5$), and grind the mixture to a fine powder. Dissolve 8.0 gm. of the powder mixture in 50 ml. of warm distilled water. If possible, allow the solution to stand overnight before using it. Upon long standing, some material may crystallize from the solution. This does not interfere with the action of the reagent. A fresh portion of this solution should be made up from the dry powder every 3 weeks.

Procedure. Measure 1 gm. of soil into an 18- by 100-mm. vial and add 10 ml. of P-A reagent. Shake this suspension for 40 seconds and filter through a dry 9-cm. paper into a *clean* funnel tube of a size fitted to the photometer. Discard the filter paper and soil when the filtration is *nearly* complete. Remove excess filtrate until 5 ml. remains in the funnel tube. Add 5 drops of P-B reagent to the funnel tube, and swirl the tube so that the reagent will be thoroughly mixed with the filtrate. Add 5 drops of P-C reagent and mix again immediately. After 15 minutes, set the funnel tube in the photometer and read the color which has developed. Use the standard curve to convert the photometer reading into pounds of phosphorus per acre.

If the color is being developed in several tubes at once, the P-B may be added to several tubes before they are mixed. When the P-C reagent is added, however, each tube must be swirled immediately afterward.

Variations of a minute or so in time of development are permissible. Observe the usual precautions for making photometric readings. The green filter can be used, in place of the red, to shorten the reading range.

With this procedure the readings of H, M, S, L, which have been used in the visual test in Illinois, correspond to the following concentrations:

L— less than 20 lbs./A.	M— 54 to 61 lbs./A.
L 21 to 26 lbs./A.	M 62 to 68 lbs./A.
L+ 27 to 32 lbs./A.	M+ 69 to 75 lbs./A.
S— 33 to 38 lbs./A.	H— 76 to 81 lbs./A.
S+ 46 to 53 lbs./A.	H 82 to 91 lbs./A.
	H+ over 92 lbs./A.

Constructing the standard curve. Standard solutions containing known con-

centrations of phosphorus are used. Phosphate solutions containing 1, 2, 4, and 10 p.p.m. phosphorus will cover the range conveniently. (With this procedure the parts per million phosphorus in solutions are converted to the equivalent pounds per acre in the soil by multiplying by 20. Thus, the standard solutions mentioned would correspond to 20, 40, 80, and 200 pounds of phosphorus per acre.) These phosphate solutions should be made up in distilled water.

Measure 5 ml. of the standards into clean funnel tubes. (A blank determination on the P-A should also be made.) Add 5 drops of P-B to each tube and mix thoroughly by swirling the tube. Add 5 drops of P-C reagent to each tube and thoroughly mix immediately afterward. With the green filter in position, set the photometer so that it reads 100 when a funnel tube of distilled water is in the light path.

Fifteen minutes after P-C reagent is added, set the funnel tubes, containing the standards, in the photometer, and record the reading for use in making the standard curve.

Plot these readings on semilogarithmic paper. Take the numbers from 1 to 10 on the logarithmic scale on the left side of the paper as photometer readings (1 = 10, 5 = 50, 10 = 100, etc.). Let the other axis represent pounds of phosphorus per acre. It is convenient to let the smallest division on the paper equal 4 pounds per acre. (The line after the first five divisions becomes 20 pounds per acre, and a scale running from 0 to 280 pounds per acre can be set up on the width of the sheet.) After plotting the readings for the standards, draw a straight line which passes through or very near to all the points.

If a solution of 0.03 *N* ammonium fluoride in 0.025 *N* hydrochloric acid is substituted for P-A in the foregoing procedure, the more insoluble types of available phosphorus are not extracted. For example, it does not dissolve rock phosphate from corn-belt soils, the solution giving a "low" test on soils that have received 4 tons of rock phosphate. Added superphosphate is detected, although added rock phosphate is not. The purpose of the solution is to extract the more highly available part of the adsorbed and easily acid-soluble phosphorus. The P-A solution, however, agrees more generally with crop response.

The amount removed from soils varying in available phosphorus by the P-A solution with a soil-solution ratio of 1-10 is about one-third of the total available phosphorus. An extraction with a soil-solution ratio of 1-50 removes more than twice as much in the same time interval. The fact that a proportionate part is extracted in each case makes it a measure of the available phosphorus.

Correlating the Phosphorus Test with Percentage Yield

The correlation of the phosphorus test with crop response was made in the same way as was the potassium test correlation. The yields and soil test values of the limestone plots (where potassium was not naturally deficient) and some LK plots were used for values y and b_1 in the modified Mitscherlich equation. The LP or LKP yields were used for A. Table 2 gives, for a number of crops, the correlations between test value and percentage yield on the plots not treated with phosphorus. Again it is demonstrated

that crops vary in their ability to feed on nutrients and give their maximum yields (98 per cent is used by the writer as a practical maximum) at different levels of available phosphorus as measured by the test. The level of the soil form needed for this maximum yield is defined as the "soil requirement" of that particular crop. The soil requirement is related only indirectly to the crop requirement, which is defined as the amount contained in the crop. For example, table 2 shows that wheat has a higher soil requirement for phosphorus than does corn, yet a corn crop contains more phosphorus than a corresponding wheat crop merely because it far outyields the wheat crop in terms of both fodder and grain on fertile soils. Table 2 is now used in Illinois to interpret soil test values in terms of a prediction of the percentage increase in yield which will follow phosphate use.

Applying the Percentage Yield Concept to Two or More Nutrients at the Same Time

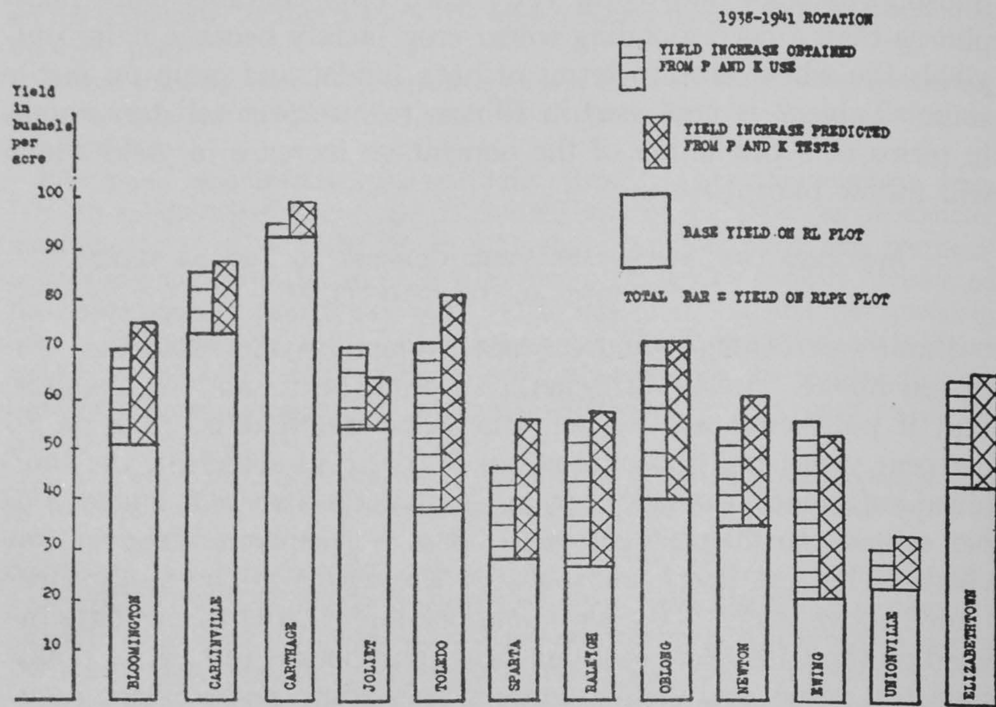
Baule's percentage yield concept is much broader than that discussed above. Using Mitscherlich's data, he found, for example, that if potassium was 80 per cent sufficient, that is, gave an 80 per cent yield, and phosphorus was 70 per cent sufficient, the combined sufficiency would be the product of the two sufficiencies (70 per cent of an 80 per cent yield) or a 56 per cent sufficiency or yield. This has been confirmed by the writer in the study mentioned above, and it has been found possible (9, 13) to calculate the yield on the LPK plots by using data (phosphorus test value, potassium test value, and yield) obtained only from the limestone plots. (See figure 2.) Thus tables 1 and 2 can be used to interpret the soil tests of a given farm field in terms not only of the single deficiencies but of their combined effect. Mitscherlich and Baule applied this concept to all nutrients, but the writer considers that it cannot be applied, for example, to nitrate nitrogen or water for reasons already given.

Practical Application of Correlations for Phosphorus and Potash

As has been mentioned, tables 1 and 2 are used in a soil-testing program in Illinois in which the tests for phosphorus and potassium just described are employed (10, 11). The soils are sampled, brought into the laboratory,[4] processed, and tested by the same procedure as that followed in obtaining the correlations.

[4] Illinois has about 65 county soil-testing laboratories.

When a farmer's field is sampled and tests are run for available phosphorus and potassium, the first step is to interpret each test in terms of the percentage yield of each nutrient. If the field does not vary sufficiently to warrant making different recommendations, the percentage yield values (not the soil-test values) for each are averaged. The average percentage yield for phosphorus is multiplied by the average percentage yield for potassium, as described in the previous section, to obtain the combined sufficiency. The dif-



Courtesy the Williams & Wilkins Co., Baltimore, Md., publishers of Soil Science

Figure 2.—Comparison of actual and calculated increases in corn yields on soil experiment fields

ference between the combined sufficiency, or percentage yield, and 98 per cent is the percentage increase in yield that can be expected as a result of making both phosphorus and potassium adequate. This value for the expected increase serves as a basis for estimating whether or not the treatment will be worthwhile. To do this, one must also know how much phosphate and potash fertilizer is needed.

CORRELATING SOIL TEST VALUE WITH FERTILIZER REQUIREMENT

The fertilizer requirement and the percentage yield possibility are not the same thing. One can calculate the percentage yield pos-

sibility without knowing anything about the fertilizer requirement. The only requirement in the percentage yield correlation is that the treated plot represent a plot adequately treated. Surplus fertilizer, provided it was not sufficient to decrease the yield, could have been added without changing the results.

Let us define fertilizer requirement as the amount of fertilizer needed to supplement the soil supply (measured by the soil test) in order to obtain maximum (98 per cent) yields. Every different soil-test value will thus have a different fertilizer requirement, and the fertilizer requirement of the same soil will change from year to year as the use of fertilizer increases the level of the nutrients

TABLE 3.—APPROXIMATE MURIATE OF POTASH REQUIREMENTS (0–0–50) OF INDIVIDUAL CROPS FOR EACH SOIL-TEST VALUE

Available potassium by test (b_1)	*Potash requirements for different crops in terms of muriate of potash* (50 per cent K_2O)		
	Corn or clovers (c = 0.0094)	Soybeans (c = 0.015)	Wheat or oats (c = 0.020)
lbs./A.	*lbs./A.*	*lbs./A.*	*lbs./A.*
40	152	94	62
60	136	84	50
80	124	72	36
100	110	62	24
130	92	46	
150	74	36	
200	40		

Courtesy the Williams & Wilkins Co., Baltimore, Md., publishers of Soil Science

in the soil, or the lack of fertilizer, accompanied by crop removal, decreases the level. The fertilizer requirement also changes with the kind of fertilizer used (super, fused, or rock phosphates, for example) and the method of application. It cannot, therefore, be so precise a value as the percentage yield.

PHILOSOPHY OF FERTILIZER USE

Interpretations of the soil tests in terms of the fertilizer requirement must be made with due consideration of the objectives involved. A philosophy of building up the fertility to maximum levels and maintaining the soil in a fertile condition is far different from the philosophy of fertilizer placement in an effort to produce the greatest yield with the smallest amount of fertilizer, though they

both may have their place. It takes a knowledge of the chemistry of soil fertility to know where that place is. Soils incapable of holding the added fertilizer, like the Florida sands, need constant additions, as well as placement methods where possible. Soils with only a small capacity to adsorb nutrients can lose these nutrients readily through leaching and may also require placement methods. With soils capable of adsorbing and storing all the nutrients except nitrate and water, as most soils can, one has a choice of building up the soil or of using placement methods to increase the efficiency of smaller amounts of fertilizer which are added.

We are thus faced with the necessity of answering a question such as this: What is the potash requirement for a corn crop on a soil testing 100 pounds in exchangeable potassium where the potash is broadcast as compared to where potash is applied in the row or hill-dropped or on the plow sole? Four different correlations for the one crop are necessary to answer this question, which means that rate of application studies with varying increments of muriate of potash must be made under varying conditions for each method of application suggested. Long-time rate of application studies, where the same plot has received regular applications, are of less value than one might think for this purpose, because the build-up in the soil is changing the soil level each year and decreasing the value of the increment yearly. Large plots which can later be subdivided, using part of a treated plot as a check to measure the response to the new increment, might solve this problem. There is little doubt, however, that the old methods of studying fertilizer needs have not solved the problem. New field experiments must be designed with the principal purpose of providing correlations between the soil tests and the percentage yields and fertilizer requirements.

Meanwhile, the investigator interested in correlating soil tests with fertilizer requirements can do effective work by using the materials already available.

For the Illinois experiment fields, where the fertilizer requirements for phosphorus or potassium have not been studied, the writer had to make certain assumptions which appear to be reasonable and which have provided fertilizer requirement tables.

Correlation of Potash Test with Fertilizer Requirement

The potash test was correlated with the fertilizer requirement by assuming that the requirements followed the law of diminishing

returns. On two of the fields, the ones lowest in exchangeable potassium, use of 400 pounds of KCl (50 per cent) each 4-year rotation had apparently given maximum yields, as shown by the fact that additional KCl on subdivided plots gave a little, but only a little, increase with some crops and none with other crops. It was then assumed that if these soils, testing approximately 50 pounds in exchangeable potassium, had a rotation requirement (4-year) of approximately 400 pounds of KCl, any soil testing less would have a higher requirement and any testing higher would have a lower requirement, and this change would follow the curve for the law of diminishing returns. This gave a rotation requirement based

TABLE 4.—APPROXIMATE SUPERPHOSPHATE REQUIREMENTS (0–20–0) OF INDIVIDUAL CROPS FOR EACH SOIL-TEST VALUE

Available phosphorus (soil-test value)	*Superphosphate requirements for different crops in terms of 20 per cent superphosphate*		
	Wheat or clovers (c = 0.0082)	Corn (c = 0.013)	Soybeans or oats (c = 0.015)
	lbs./A.	*lbs./A.*	*lbs./A.*
Low—	167	91	75
Low	154	75	58
Slight—	132	50	36
Slight	120	36	27
Medium—	86	13	
Medium	68		
Medium+	22		

Courtesy the Williams & Wilkins Co., Baltimore, Md., publishers of Soil Science

on broadcasting most of the potash for legumes and hill-dropping a part for corn, as had been practiced on the experiment fields. The rotation requirement table for potassium, for rotations similar to those grown on the experiment fields, is given in table 3, which shows not only the requirement but also the average percentage yield for the rotation. All general use of fertilizer in Illinois is based on these rotation requirements. Special placement applications for special effects are credited to the rotation requirement. They are based on a philosophy of providing the highest build-up of available potassium and obtaining the highest return per acre—not on getting the highest return per dollar or unit of potassium, which is usually accompanied by the lowest build-up of available potassium in the soil.

Correlation of Phosphorus Test with Phosphate Fertilizer Requirements

The correlations of the phosphorus test with fertilizer requirements for both superphosphate and rock phosphate are given in table 4. They were obtained by making the same assumptions as were made for the potassium test (13). They are less satisfactory than the potassium test correlations, however, because there are no data to show that the superphosphate was used in adequate amounts. The superphosphate requirements given in table 4 may not be quite large enough. An indication of this is that they are very close to maintenance needs for the system of farming to which they are being applied.

LIMITATIONS OF PERCENTAGE YIELD AND FERTILIZER REQUIREMENT TABLES

How far can one apply such correlations as have been described? Soil variables such as texture, base-exchange capacity, nature of the clay mineral, degree of saturation with bases, organic matter, and physical condition of the subsoil are all supposed to influence yield, availability of the nutrient, and need for fertilizers. Apparently these soil variables do not affect the two foregoing correlations so much as has been hypothecated, because a wide range of all these variables except that of mineral nature are present in these studies (12). The Tennessee work gives somewhat similar percentage yield values (18). Evidently the influence of all other soil properties on the availability of a given form of a nutrient has been overestimated as compared to the significance of the *amount* present.

This does not mean that soil properties do not influence these correlations; it means only that the influence is not sufficient to make practical correlations impossible where these correlations are for a growth factor varying as much as 600 per cent in different soils. The interpretations in tables 1 to 4 are being applied strictly to the conditions represented in the original correlation, although so far as is known, they may be satisfactory for the whole corn belt and, perhaps, for eastern and southern soil conditions. The correlations obtained so far are for situations in which the sufficiency has not fallen below 50 per cent for any one nutrient. Whether or not the percentage yield concept holds accurately for more severe deficiencies is not known.

Soil-test values are a measure of the amount of an available nutri-

ent in a soil. Soil-test correlations relate this amount to the growth and response of each crop. They are most accurately applied in practice to conditions similar to those under which the correlations were made. When the available form being measured is common to a wide variety of soils, however, soil tests can be applied rather widely. Thus it is accepted, for example, that exchangeable potassium is the dominant available form in virtually all well-drained soils. A test which gives an accurate measure of the total exchangeable potassium can be used for virtually every soil in this country. It is only the correlation that may have to be changed for variations in crop, soil, and climate.

Table 1 illustrates the need for different correlations for different crops. But it also illustrates that one would not be far wrong in calling a 150-pound potassium test a "high" test, because it is sufficient for a 90 per cent yield, or better, of every crop listed. One could also expect it to be a "high" value of such crops as barley and rye because these crops are so similar to oats and wheat. On the other hand, the yield of corn planted twice as thick as the two to three per hill in hills 40 inches apart each way, the rate used in the original correlation, should be cut more than 10 per cent if only 150 pounds were present.

To obtain new correlations, one does not have to change, for example, the extracting solution or technique of a test that is a measure of the total available supply, as is the potassium test described above. All one needs is samples from deficient experiment field plots whose response to adequate potassium is known.

If these correlations are properly made, using soil tests or methods that are a measure of the total available nutrient supply, there need be no special limitations in their use other than those involved in *every method* of determining or making fertilizer recommendations. In other words, a correlation depends for its accuracy, once the quantitative aspect is satisfied, on the accuracy of the field work itself. Factors which adversely influence field results are not eliminated when the field data become part of the soil-test correlation. Formerly, many agronomists considered soil tests impractical because other factors were influencing yield besides the nutrient supply in the soil. Also, because correlations could not be obtained, they blamed the soil-test values instead of the field data. Many tests measured directly independent factors in crop growth. This is not true of most experiment field work. Fertilizer trials, at best, are crude measures of fertility, and the response of a plant is not

the most accurate measure of the available nutrient supply in the soil, as most agronomists have assumed in the past.

It is a fact, however, that the soil tests measure the fertility in the soil far more accurately than can the plant. Table 1 shows that 400 pounds of exchangeable potassium (200 p.p.m.) for each 2,000,000 pounds of soil is an excess; 300 pounds is about right for a 98 per cent yield of corn; 150 pounds is sufficient for a 90 per cent yield; and 50 pounds gives only 53 per cent of the yield possible with adequate potassium.

Now let us consider how accurately field trials can measure this range. The plant cannot indicate excess potassium; its response does not change as the potassium decreases to 300 pounds; experimental errors prevent an accurate measure of the decline to a 90 per cent yield as the potassium decreases to 150 pounds; but a further decrease from 150 to 50 pounds is measurable by field techniques although subject to the same degree of experimental error as before. It is this latter range of response which must be studied in order to obtain the data for soil-test correlations. It is, therefore, only from mediumly to highly deficient soils that sufficiently accurate field data can be obtained for soil-test correlations. But once the correlations are made, the tests can be used to measure the whole range of deficient and excess fertility. Field work, designed especially for these correlations, is much needed in all states, not only for potassium and phosphorus, but for the other nutrients as well.

PRACTICAL INTERPRETATION OF PERCENTAGE YIELD VALUES

If, for example, a soil tests 80 per cent sufficient in potassium and 70 per cent sufficient in phosphorus (tables 1 and 2), according to soil-test values obtained on his field, what does this mean to the farmer? In the first place, it means phosphorus and potassium are limiting yields so that only 80 per cent of a 70 per cent yield, or a 56 per cent yield, is being obtained, so far as phosphorus and potassium are concerned. No implication as to how large or how small this yield may be is involved if the interpretation is to be made for situations similar to the ones involved in the original correlation. Therefore, it may be a 40-bushel yield of corn or a 100-bushel yield, after phosphorus and potassium are applied, but without phosphorus or potassium it will be 56 per cent of either a 40-bushel yield or of a 100-bushel yield. For the average seasonal condition, use of phosphorus and potassium in adequate amounts

can increase the farmer's yields from 56 to 98 per cent which, *based on the treated yield*, is an increase of 42 per cent. This percentage varies somewhat with seasonal conditions but since the farmer grows crops every season, he is farming an average season over the years. This percentage increase is the basis for deciding whether or not the fertilizer needed will pay its way. If the productive possibilities of a soil are so low that an average annual use of about $3 worth of phosphorus and potassium cannot be paid for out of a 42 per cent increase (almost doubling the yield), then fertilizer use will not be worth while. It might also be pointed out that if 42 per cent of the final yield is not worth $3, it is not worth while farming the land in the first place. This is where knowledge of local conditions is needed, and the county agent or similar worker is the best person to make the final interpretations for fertilizer use. He should know the farm setup, the crops grown, the soil types and their productive possibilities, the farmer's financial situation, and a number of other items before trying to integrate the fertility program with the whole farm program.

He must, above all, make sure that the phosphorus and potassium are being used with an otherwise sound fertility program. He should understand the elasticity concept in soil fertility and the limitations in both the percentage yield concept and Liebig's law of the limiting nutrient. He should know that only the immobile nutrients like phosphorus and potassium are highly elastic, have a wide variable yield possibility, and are not readily leached. Also, that nitrate nitrogen is much less elastic and that a given amount can produce only a variation in yield as wide as the variation in crop composition will permit. In short, the 42 per cent increase estimated for phosphorus and potassium in the foregoing example will not occur, even if there is adequate water, unless either additional nitrogen is added or enough for the increase in yield will be liberated by the soil. Elasticity of use of nitrogen by internal "stretch" within the plant is not sufficient to permit almost doubling the yield where the nitrogen supplied by the soil is just about sufficient for the original yield before phosphorus and potassium are added. So, although tables 1 and 2 give definite percentage yield values and follow the Baule percentage yield concept, they must be interpreted in light of other factors in fertility. Factors such as nitrogen and water must be present in quantities adequate for the final yield possibility, and phosphorus and potassium cannot be expected to give responses on soils incapable of furnishing the

extra nitrogen and water needed for the increase. Phosphorus and potassium, even where highly deficient, should be recommended only along with an otherwise complete soil fertility program.

The one who makes the final recommendation to the farmer should know that, because phosphorus and potassium, for example, work on a percentage basis, it is the nitrogen and water supply, the season, and the physical condition of the soil which are the factors that control the absolute productivity level. He should be able to distinguish between the chemical fertility factors in the soil and the physical productivity factors. The only reason good soil-test correlations for phosphorus and potassium were obtained on the Illinois fields was because all the rotations included legumes. Once this crop was under way, the increase in its growth, when a deficient nutrient was added, provided extra nitrogen needed for the increase in yields of other crops caused by the addition of the nutrient. It might be pointed out that legumes follow more fully than other crops the percentage yield concept because they fix their own nitrogen, and their increase in yield for phosphorus or potassium will not be so limited by nitrogen. In fact, it might be further pointed out that Nature tries to follow the percentage yield concept even with respect to nitrogen, because in naturally fertile soils a large supply of humus is present. In favorable seasons more nitrogen is released, thus enduing nitrogen with a partly elastic availability. In soils low in organic matter, on the other hand, nitrogen always acts as an inelastic nutrient.

Under one philosophy of fertilizer use, that is, the philosophy of building up the fertility in the soil, which is applicable to soils having good adsorptive properties, as do most soils, determination of exact fertilizer requirements is not necessary, provided the test can be interpreted in terms of percentage yield or sufficiency. If the objective of phosphorus and potassium use, for example, is to achieve maximum yields and at the same time build up the soil level, sufficient is already known about fertilizer use to enable us to choose an amount that can accomplish this purpose for any given nutrient level as long as we do not insist that the amount be *exactly* adequate any one year. A more than adequate amount of fertilizer, yet not harmful, leaving a wide range to choose from, can be added at first, and the soil test can then be applied to regulate its use. When the levels of the soil forms are built up to those needed by the crops (the soil requirement, or 98 per cent yield level) the amounts are then reduced to maintenance levels. If

the build-up lags behind, the amounts can be increased, or vice versa.

In short, now that we have soil tests to measure changes in soil fertility and as long as the nutrients and soils are of a nature which prevents significant losses of the nutrient, figures on exact fertilizer requirements are not needed, and fertilizer use can be controlled by the tests. For most general use, therefore, the percentage yield correlation of the test is the most valuable. Furthermore, it is a correlation that can be achieved for one crop and one nutrient with a single pair of plots replicated sufficiently to cover different soil conditions in the areas to which the interpretations are to be applied.

FIELD DESIGN FOR CORRELATING RAPID SOIL TESTS AND CROP RESPONSE

When satisfactory experiment fields are not available, the possibility of establishing tentative practical correlations in one year for a wide variety of soil conditions can be studied with few plots compared to those in the usual experiment field setup. It is known that different crops respond differently in fertilizer studies, and it has also been shown that they maintain their relative difference over a wide variety of soil conditions (13). This indicates that one could study the relation of a soil-test value to the response of one key crop under variable soil conditions and establish whether or not a constant or virtually constant c_1 value holds for the varied soil conditions included in the study. If, for a given crop, an average c_1 value in the equation

$$\log (A-y) = \log A - c_1 b_1$$

is found to apply, practically, to a wide variety of soil conditions, it means that soil testing can be applied practically to this crop in the whole area. If so, it will probably be possible to find correlations for the rest of the crops grown. Two or more different c_1 values for the same crop, as long as the soil conditions which lead to the different c_1 values can be identified and separated, would also be of practical value.

If a c_1 value for one crop can be established for any one large area, the c_1 values for similar crops might not have to be established, provided they were known for other areas. For example, where the relative c_1 values for corn, oats, and wheat are known, as in Illinois, they might hold for other areas, although the absolute values might be different. It has not, however, been established, either that c_1 does change appreciably from area to area or, if it

does, that the values for other crops would also change correspondingly.

To make such a study, it is only necessary to treat one plot so that *all* nutrients are adequate or in excess but not in harmful excess. Nitrogen can be controlled with tissue tests, the other nutrients with the soil tests, so that harmful excess can be avoided. An adjacent plot receives the same treatment except that the nutrient studied is omitted from the treatment. The yield on the first or fully treated plot is A in the foregoing equation. The yield on the second plot is y, and the soil-test value of the plot for the omitted nutrient is b_1, provided the test value is a measure of the total supply of the available form of the nutrient. Since the object is to determine whether or not soil testing can be applied to a whole area in a practical way, replication of these two adjacent plots within the same field can be limited to three or four so that a greater number of soil conditions can be included.

The soil test should be used to select fields *varying widely in soil-test value* and also varying in other properties. Sands, silts, and clays, if present and used for growing the key crop, should be included. For example, in the Southeast, both Piedmont and Coastal Plain areas may be included. Permanent or temporary plots can be used. With temporary plots in farm fields the studies can be shifted to other fields each year so as to include more variables.

Such a study has already been made for phosphorus in the Cook County (Illinois) vegetable growing areas with tomatoes.[5] The soils were selected to include different soil conditions and different soil-test values, from "low" to "high." An excellent tentative correlation was obtained in one year with two replications on eight different fields varying greatly in yield. A second year's results with three replications on seven new fields verified exactly the first year's results. Four replications on ten new fields in the third year confirmed the previous work. This established the sufficiency for tomatoes of the different levels of soil phosphorus as measured by the soil test and served as a basis for varying the fertilizer requirement from maximum on the low-testing soils to none on the high-testing soils. A fertilizer application which had given maximum yields on the low-testing soils was used as the base and scaled down, along the Mitscherlich curve. But to establish the more exact fertilizer requirement for each soil-test value, a fertilizer rate study is also needed. It can be included with the aforemen-

[5] Arnold, C. Y. Unpublished work. Dept. Hort., Univ. Ill. 1947.

tioned study through addition of extra plots adjacent to the sides and corners of the untreated plot and treated with varying increments of the nutrient studied but otherwise treated similarly. Where the number of plots must be restricted, an effort should be made to include soils of known differences in productivity. The data are then substituted in the following equation:

$$\log (A-y) = \log A-(c_1b_1+cx)$$

where c_1 has already been solved for with the previous equation, c is the constant for the fertilizer used, and x is the increment or amount of fertilizer added. The c is, of course, a constant for the nutrient carrier used and the method of application.

Too much emphasis cannot be placed upon the necessity of keeping the plots adjacent to one another. Preferably, the plot giving yield y (no nutrient added), from which b_1 is obtained, should be a middle plot, with the plots receiving the various increments adjacent to the four sides and four corners. Randomization of the plots within this set must be avoided. The object of randomization is to include possible unknown variables. The object of having the plots adjacent is to eliminate unknown variables as much as possible so that the difference in yield will be due to variations in the nutrient studied. Because the soil tests can now measure so many of these formerly unknown variables, the reasons for randomization of treatments in experiment field plans should be thoroughly reviewed in the light of this new tool in field experiment studies. The fact that one can, through the soil tests, treat data from twenty-three different experiment fields on varying soil types distributed over the whole state of Illinois, using each field as though it were a plot, or rather a pair of plots, and using the whole state as though it were an experiment field on a single soil type, as was done by the writer (12, 13), points to a need for acceptance of the value of quantitative studies of the available nutrients as the basis for establishing many types of field studies.

It is realized that the foregoing suggestions for rapidly establishing tentative practical correlations imply the need for experienced research men to plan the treatments so that harmful excesses will be avoided.

NUTRIENTS OTHER THAN POTASH AND PHOSPHORUS

The potash and phosphorus tests have been used to illustrate the possibilities of soil testing because they are the only rapid tests that have been widely correlated with crop response and fertilizer

needs in a practical way. Limited correlations of tests for other nutrients have been obtained, however, in various parts of the country.

Exchangeable magnesium and calcium are easily measured in the extract used for the potassium test. Directions for determining the amounts present in the extract will be found in another chapter in this book (p. 6 *et seq.*). These directions can, in general, be applied to the potassium-test extract described in this chapter, and similar directions need not be duplicated here, since they involve only qualitative and quantitative chemistry, not soil chemistry.

Calcium

It is doubtful whether one can find a general correlation between exchangeable calcium and crop needs in normal carbonate-free soil. Calcium performs two functions, that of an essential nutrient and that of controlling soil acidity or pH. Usually the amount of calcium needed to neutralize the soil to a favorable pH is more than adequate for crop needs.

Only in soils with a very low exchange capacity, usually one containing the kaolinitic type colloid, or with crops requiring a very high acidity, is the need for calcium as a plant nutrient likely to be greater than its need as a control of acidity. Amounts of potassium and magnesium sufficient for a favorable pH could be present. but they would overbalance the usual ratio of these three nutrients. For example, the sum of the potassium and magnesium could be larger than the calcium and the pH could be favorable, even though calcium was deficient. This could easily occur on a kaolinitic type soil with a low exchange capacity. The writer has, however, found exchangeable potassium higher than calcium in the potato soils of Maine, where acidity is desired. Whether it was high enough to cause a calcium deficiency was not determined.

Magnesium

Magnesium also helps control the acidity of the soil, but where calcium assumes the dominant role, a good soil-test correlation should be possible for magnesium. Roughly, soils containing less than 100 pounds per acre of exchangeable magnesium are probably deficient in magnesium. Percentage yield correlations have not been worked out.

Sulfur

By addition of $BaCl_2$, excess sulfur is easily determined in the

filtrate used for the potassium test. Normal soil, not deficient in sulfur, gives only a trace of sulfate in the filtrate, and no definite correlations with crop needs are known.

The Minor Nutrients

Iron and Manganese. Iron and manganese appear to be definitely connected with the base-exchange complex, especially in acid soils. They also occur as concretionary material associated with the clay or as small to large individual splotches or concretions. Virtually all extraction solutions suggested for soil tests extract some of each, but the amounts vary with the concentration and acidity of the extracting solution. No quantitative measures of the "available forms" of these minor nutrients have been devised. Positive tests can often be interpreted as indicating a sufficiency, but negative tests may or may not indicate a deficiency.

Boron. Water-soluble boron, such as measured by the Berger and Truog method (2), has been used in studying boron deficiency. When less than 0.5 p.p.m. of boron is found in the soils of southern Illinois, for example, alfalfa shows boron-deficiency symptoms which can be corrected by the addition of 30 pounds of borax per acre. This illustrates the application of an arbitrary procedure which gives practical results for a special situation, although little is known about the forms of the boron compounds being measured. The test requires both high skill and special glassware. It is not adapted to routine running by semiskilled help and has, at present, more the aspect of a laboratory determination than of a rapid soil test.

Copper and Zinc. Little is known about the available forms of copper and zinc, although both elements would be expected to react with the base-exchange complex. Special methods for extracting quantitatively their available forms have as yet not been designed. When they are, the small amounts of zinc and copper in the extract may have to be measured with the spectrograph rather than by simple chemical tests.

General Discussion of the Minor Nutrients. Not enough is known about how to extract the available forms of the minor nutrients to warrant recommendation of any one extracting solution for making general soil-test correlations. This does not mean that some of the extracting solutions already in use cannot be employed for special local situations, especially where a spectrograph is available for measuring the nutrient in the extract. Often an extracting

solution may be inferior for general use, yet may be useful for a special, local situation. For example, Morgan's "Universal" solution, used by Peech and English (17) and by other investigators to extract the available phosphorus in soils, has been found useful for very limited correlations for some soils in the eastern part of the country. On the other hand, it has been shown to extract virtually no phosphorus from the rich soils of the corn belt not responding to phosphorus. Such a solution can be useful for a limited correlation, yet its recommendation generally for soil testing would be dangerous.

Nitrogen

The available forms of soil nitrogen are mainly nitrate and ammonium nitrogen. These are not storage forms in the soil and do not generally accumulate in large amounts. The ultimate available form taken up by plants is nitrate nitrogen, although in many soils some ammonium nitrogen occurs and is utilized by plants. Under normal conditions, tests for nitrate nitrogen measure the available nitrogen of the soil.

Interpretation of Soil Tests for Nitrate Nitrogen

Insofar as a test is sufficiently quantitative, it is a measure of the amount of nitrate nitrogen in the soil. This amount is not, however, as in the case of available potassium or phosphorus, any indication of the ability of the soil to supply nitrogen to plants. The whole year's supply of available nitrogen is not present in the soil at the start of the growing season, as can be the case with the other nutrients. True, some accumulates in the warm spring before crops become large enough to remove it. But the amount present in spring has no direct relation to the ability of the soil to supply nitrogen during the rest of the growing season. Once the crop has decreased the nitrate nitrogen to a minimum, it may still continue to grow adequately, although the amount of this nutrient in the soil at any one time may not be more than 5 to 10 pounds. Nitrate nitrogen is so soluble and mobile that it can be said to be almost 100 per cent available. The small amounts released each day by the soil organisms may, therefore, keep the plants growing adequately, although no accumulation of nitrate nitrogen in the soil occurs.

Because of this situation, nitrate nitrogen cannot be interpreted in terms of a certain percentage sufficiency, as can phosphorus and potassium. Whereas 200 pounds of exchangeable potassium, for

example, can be approximately sufficient for 95 per cent of either a 50-bushel crop or a 100-bushel crop, a certain amount of nitrate nitrogen in the soil can be sufficient for only a certain number of bushels and does not represent or indicate the total amount of nitrogen finally afforded the crop.

"Negative" tests are usually found under corn during the growing season on corn-belt soils, although the final yield may be over 100 bushels an acre.

It appears that plant-tissue tests are the solution to nitrogen control. A positive test for nitrate nitrogen in the tissues is an indication that the plant is receiving at the time good amounts of nitrate from the soil. With many plants, a negative test means that sufficient nitrate nitrogen is not being supplied.

Sometimes negative tests develop early enough that more nitrogen can be sidedressed in soluble forms. In other cases, the negative test may develop late in the season during the reproductive stage when nitrogen application may not be practical because of dry weather.

In Illinois, the powder tissue test for nitrogen, described below, has been found highly practical as a guide to nitrogen needs. The reagents can be safely carried in one's pocket, ready for instant use. The test helps explain many of the things that are happening in the field. It points out where a farmer's nitrogen-legume program is not adequate for obtainable yields and, even though the negative test develops too late to allow any correction during the current year, it has shown up a weakness in the cropping and fertilization program which needs to be corrected.

The soil test for nitrate nitrogen is described below because it has certain uses (15). Measuring and controlling the nitrate level in garden or greenhouse soils, especially to avoid excesses, is one of these. Determining the spring accumulation, previous to planting and fertilization, may be of value in helping to determine how much soluble nitrogen should be included in the initial application of fertilizer. But each use of the test will be a special application for a particular situation.

Tests for Nitrates in Soils and Plants

Method 1.

Reagent 1. (a) 100 gm. $BaSO_4$
(b) 1 gm. finely powdered zinc
(c) 10 gm. $MnSO_4 \cdot H_2O$

The reagents should be free of nitrate and nitrite. Thoroughly grind them together, making a nearly white powder.

Reagent 2. Ten per cent acetic acid made nitrate-free by addition of a little powdered zinc.

Reagent 3. To 50 ml. of reagent 2 add approximately 0.25 gm. (size of a pea) of a mixture of equal parts by weight of alpha-naphthylamine and sulfanilic acid.

Reagent 4. A standard nitrate solution (100 p.p.m. of N).

Procedure 1—For soil extracts or solutions. Take 5 gm. of soil and 10 ml. of reagent 2 (or any salt or acid-extracting solution, in any proportion, which will not interfere with the test). Shake together 1 minute and filter. To 1 ml. of the soil extract add 7 ml. of reagent 2 and, with a measuring spoon, ½ ml. of reagent 1. Shake immediately for exactly 20 seconds. Add immediately 1 ml. of reagent 3 and allow to settle. Read the color by comparing it with a series of nitrate standards developed in the same way. The colors fade slowly on standing. A set of permanent standards (calibrated with nitrate standards) can be made with acid fuchsin in 1 per cent acetic acid, saturated with camphor.

Procedure 2—For use without filtering. To 1 gm. of soil (or a similar volume of finely cut plant tissue), add ½ ml. of reagent 1, then add 7 ml. of reagent 2 and immediately shake for exactly 20 seconds. Allow the mixture of soil and powder to settle, and add 1 ml. of reagent 3.

Read the colors by comparing them with those produced by testing similar soils containing known amounts of nitrate or standards based on such colors. This is necessary because the color obtained is less than that produced in the absence of soil. This method is more rapid but less accurate than procedure 1.

Method 2 (powder method).

Reagent 5 (nitrate test powder).

(a) 100 gm. $BaSO_4$	(d) 75 gm. citric acid
(b) 10 gm. $MnSO_4 \cdot H_2O$	(e) 4 gm. sulfanilic acid
(c) 2 gm. finely powdered zinc	(f) 2 gm. alpha-naphthylamine

Grind any coarse materials to a fine powder. Mix b, c, e, and f *separately* with portions of the $BaSO_4$. Then thoroughly mix the whole, including a and d. Use extreme care to have room, table tops, and equipment free of nitrate and nitrite. Store the powder in a thoroughly blackened bottle. Alpha-naphthylamine is affected by light but will keep several years in a bottle coated on the outside with black paint.

Procedure 3. To 1 ml. of soil extract, obtained as described under procedure 1, add 6 ml. of distilled or nitrate-free water and ½ ml. of reagent 5. Shake for 25 to 30 seconds, and allow to settle. Read colors as in procedure 1.

Procedure 4. A rough test for soil nitrate can be made by measuring 1 ml. of reagent 5 and 1 gm. of soil into 7 ml. of distilled water. Shake this for 25 to 30 seconds, and allow it to settle. The test run in this way will not be very sensitive and is recommended only for preliminary exploratory work.

Procedure 5. Shake 1 measure of finely chopped plant material, 1 measure of reagent 5, and 14 measures of distilled water for 25 to 30 seconds and allow to settle. Read colors as in procedure 2.

Procedure 6. Split open or break off succulent plant tissue, apply a thin layer of reagent 5 to the freshly exposed surface, and squeeze material until

the plant juices have wet the powder. Nitrates in the tissue are indicated by the powder's turning pink.

Method 1 is sensitive to 1 p.p.m. of nitrate in solution yet covers a fairly wide reading range up to 35 to 50 p.p.m. When filtered and read in a photometer, replicates are reproducible to within 1 to 3 p.p.m. of nitrogen in the range of 5 to 30 p.p.m. In this respect the method is superior to the diphenylamine test usually used as a spot plate test and which, although sensitive to traces of nitrate, is not specific and is difficult to read with much more than a plus or minus designation.